Journal of Engineering and Technology for Industrial Applications

ISSN ONLINE: 2447-0228

ITEGAM-JETIA

Manaus, v.11 n.52, p. 261-265. March./April., 2025.
DOI: https://doi.org/10.5935/jetia. v11i52.1695

RESEARCH ARTICLE OPEN ACCESS

QUANTUM COMPUTING: APPROACHES, SCALABILITY, AND THE FUTURE OF EMERGING TECHNOLOGIES

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ARTICLE INFO

Article History
Received: March 13, 2025
Revised: March 20, 2025
Accepted: March 15, 2025
Published: April 30, 2025

Keywords:
Quantum Computing,
Nuclear Magnetic Resonance,
MRV,
Educational Quantum Computing.

ABSTRACT

Quantum computing is an emerging field that promises to revolutionize science and technology by offering exponentially superior processing capabilities compared to classical computing. This paper analyzes three main approaches to quantum computer development: IBM's scalable and modular systems, D-Wave's practical solutions for optimization problems, and Nuclear Magnetic Resonance (NMR)-based computers designed for education and research. We explore the technological advancements, practical applications, challenges, and future prospects of these approaches, demonstrating how they collectively pave the way for a future where quantum computing becomes indispensable.

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I. INTRODUCTION

Quantum computing is fundamentally redefining the limits of science and technology. Unlike classical computing, which operates with binary bits (000 or 111), quantum computing uses qubits. These units of quantum information exploit unique properties of quantum mechanics, such as **superposition**, **entanglement**, and **quantum interference**, enabling calculations to occur simultaneously across multiple states. This exponential processing power positions quantum computing as a revolutionary tool to address scientific, industrial, and societal challenges previously considered insurmountable [1].

The potential applications of quantum computing are vast, encompassing areas like molecular simulation for drug and material design, highly secure quantum cryptography systems, logistical optimization, and large-scale data analysis. However, realizing this potential has required the development of different approaches to harness the principles of quantum computing for practical and theoretical advancements.

In recent years, three main approaches have emerged:

1. **IBM** focuses on scalable, hybrid quantum-classical systems, striving to solve large-scale, high-complexity problems. The company has pioneered milestones such as the Eagle (127 qubits) and Condor (1121 qubits) processors and aims to build systems exceeding 4000 qubits by 2025 [2].
2. **D-Wave** specializes in optimization solutions, addressing specific industrial challenges with practical and immediate applications. Systems like Advantage2, with over 1200 qubits, have proven instrumental in logistics and geophysics [3].
3. **NMR-based quantum computers** provide an accessible entry point for education and research, allowing students and scientists to explore fundamental quantum principles [4].

While these advancements are remarkable, quantum computing still faces significant challenges, including **error mitigation**, **coherence maintenance**, and **scalability**. Additionally, Additionally, democratizing access to this technology by reducing costs and increasing availability remains a critical barrier [5].

This paper presents a comprehensive analysis of these approaches, discussing their contributions to advancing science and industry and their potential to shape the future of technology. IBM leads with scalable solutions, D-Wave delivers practical results, and

NMR systems provide educational opportunities, collectively transforming quantum computing into a foundational technology of the 21st century.

II. THEORETICAL REFERENCE

II.1 QUANTUM COMPUTING OVERVIEW

Quantum computing relies on qubits, the fundamental units of quantum information, which differ from classical bits due to their ability to exist in a superposition of states [4]. Mathematically, a qubit is described as a linear combination of two basis states, represented as ∣0⟩ and ∣1⟩, defined by the equation [5]:

$$|\psi\rangle=\alpha|0\rangle+\beta|1\rangle, \text{ where } |\alpha|^2+|\beta|^2=1 \quad (1)$$

This property allows qubits to process multiple states simultaneously, resulting in exponentially greater computational power compared to classical bits.

Qubit scalability is a critical factor in quantum systems' performance. While classical systems are limited to linear state processing, quantum systems can represent 2n2^n states simultaneously, where nn is the number of qubits. For example, a system with 5 qubits can represent 32 states simultaneously, while a 1000-qubit system can explore $210002^{(1000)}$ states.

Table 1: Classical and Quantum Capability Comparison.

Number of Qubits	Classical Capability	Quantum Capability (2^n)
2	2 states	$2^2=4$ *states*
3	3 states	$2^3=8$ **states**
5	5 states	$2^5=32$ *states*
1000	1000 states	2^{1000}

Source: Authors, (2025).

Table 1 illustrates a comparison between the capabilities of classical and quantum systems, highlighting the exponential growth of quantum computational power relative to classical systems. While a classical system with n bits can represent n states, a quantum system with n qubits can explore 2n2^n2n states simultaneously, as shown in the table. For instance, 5 qubits allow access to 32 states at once, whereas 1,000 qubits can explore 2^{1000} states, demonstrating the superior scalability of quantum systems.

These properties make quantum computing ideal for solving problems deemed intractable for classical computers, such as molecular simulations, industrial process optimization, and advanced cryptographic algorithms.

II.2 TECHNOLOGICAL APPROACHES

Three distinct technological approaches are shaping the development of quantum computing: IBM's scalable systems, D-Wave's optimization solutions, and Nuclear Magnetic Resonance (NMR)-based systems for education and research. Each approach has unique focuses, features, and challenges.

II.2.1 IBM: SCALABLE MODULAR SYSTEMS

IBM leads innovation in hybrid quantum systems, integrating classical and quantum processors to tackle high-complexity problems [6],[7]. Highlights include:

- **Advances:** Processors like Eagle (127 qubits) and Condor (1121 qubits), aiming for over 4000 qubits by 2025.
- **Applications:** Molecular simulations for drug development, material modeling, and artificial intelligence algorithms.
- **Challenges:** Error mitigation and quantum coherence maintenance in large-scale systems.

II.2.2 D-WAVE: PRACTICAL OPTIMIZATION SOLUTION

D-Wave adopts a specialized approach, focusing on optimization problems via quantum annealing. Key features include:

- **Advances:** The Advantage2 system with over 1200 qubits, providing practical solutions to industrial challenges.
- **Applications:** Logistics, such as supply chain optimization, and geophysics, including subsurface mapping.
- **Challenges:** Limited scalability and inability to execute universal algorithms【94†source】.

II.2.3 NMR-BASED QUANTUM COMPUTER

Nuclear Magnetic Resonance (NMR)-based systems offer an accessible alternative for teaching and research in quantum computing. Main characteristics:

- **Advances:** Models like SpinQ Gemini (2 qubits) and Triangulum (3 qubits), accessible for academic use.
- **Applications:** Teaching fundamental algorithms like Grover's and Deutsch-Jozsa, and experimenting with basic quantum principles.
- **Challenges:** Limited scalability and precision, hindering large-scale practical applications.

III. TECHNOLOGICAL APPROACHES

III.1 IBM: SCALABLE MODULAR SYSTEMS

IBM is recognized for its leadership in developing scalable, modular quantum processors that address complex scientific and industrial needs [8],[9].

- **Advances**:
    - Launch of the Eagle processor (127 qubits) in 2021, followed by the Osprey (433 qubits) in 2022 and Condor (1121 qubits) in 2023.
    - A roadmap targeting over 4000 qubits by 2025 through modular architecture that combines multiple quantum processors.
- **Applications**:
    - **Molecular Simulations**: Designing new drugs and materials through precise chemical simulations.
    - **Artificial Intelligence**: Developing advanced algorithms for big data analysis.
- **Challenges**:

- **Error Mitigation**: Ensuring reliability in large-scale quantum operations.
- **Coherence Maintenance**: Preserving quantum states in complex systems.
- **Integration**: Combining classical and quantum systems effectively.

III.2 D-WAVE: PRACTICAL OPTIMIZATION SOLUTIONS

D-Wave distinguishes itself by focusing exclusively on optimization problems, providing practical tools for real-world industrial challenges [3].

- **Characteristics**:
    - Advantage2 system, with over 1200 qubits, offers 20 times greater performance for complex optimization problems.
    - Utilizes quantum coupling technology to address logistical and geophysical challenges.
- **Applications**:
    - **Geophysics**: Partnerships with companies like Aramco for seismic data processing and detailed subsurface mapping.
    - **Logistics**: Supply chain optimization and resource allocation.
- **Challenges**:
    - **Limited Scope**: Optimized for specific problems, lacking capabilities for general quantum algorithms.
    - **Scalability**: Expansion depends on hardware and error mitigation advancements.

III.3 NMR-BASED QUANTUM COMPUTERS: EDUCATION AND RESEARCH

NMR-based systems provide an alternative for education and research, leveraging nuclear spin qubits manipulated through radiofrequency pulses [5].

- **Characteristics**:
    - Models like the SpinQ Gemini (2 qubits) and Triangulum (3 qubits) enable basic quantum operations.
    - Designed to democratize access to quantum computing for academic institutions.
- **Applications**:
    - **Education**: Introducing fundamental quantum algorithms, such as Grover’s and Deutsch-Jozsa.
    - **Research**: Validating quantum theories and experimenting with quantum principles.
- **Challenges**:
    - **Limited Scalability**: Restricted to small systems.
    - **Precision**: Challenges in maintaining coherence and achieving stable results.

III.4 GRAPH GENERATION DESCRIPTION

To visualize the comparative analysis of quantum technologies, a graph was created using Python and the Matplotlib library. The graph highlights two key evaluation criteria: scalability and impact on applications, for IBM, D-Wave, and NMR technologies. The following steps outline the methodology used to generate the visualization:

- **Data Preparation:**
    - A dataset was defined, representing the scalability and application impact of each technology on a scale from 1 to 10.
    - Scalability refers to the capacity of each technology to expand its qubit count and handle complex problems.
    - Impact evaluates the practical relevance of the technologies in scientific, industrial, and educational contexts.
- **Graph Configuration:**
    - A two-dimensional scatter plot was chosen to represent the data.
    - Each technology (IBM, D-Wave, and NMR) was assigned a unique color for visual distinction.
- **Labeling and Customization:**
    - Labels were added to each point on the graph to identify the technologies.
    - The graph was customized with appropriate titles, axis labels, and a grid for better readability.
- **Execution Environment:**
    - The graph was generated in a Python environment with the Matplotlib library, ensuring compatibility and reproducibility.
- **Visualization Output:**
    - The resulting graph illustrates the distinct characteristics of each technology, emphasizing IBM's scalability, D-Wave's practical applications, and NMR's accessibility for research and education.

The graph provides a clear visualization of the comparative analysis, highlighting the unique roles of IBM, D-Wave, and NMR-based quantum technologies in advancing quantum computing. This approach ensures transparency and reproducibility while avoiding the direct inclusion of source code in the article.

IV.COMPARATIVES ANALYSIS: IBM, D-WAVE, AND NUCLEAR MAGNETIC RESONANCE (NMR) QUANTUM COMPUTING

The comparative analysis of quantum technologies was conducted based on specific criteria evaluating their features, applications, and limitations. This section outlines the methods used to collect, organize, and analyze data on IBM, D-Wave, and NMR-based systems.

IV.1 EVALUATION CRITERIA

The comparison of technologies followed three main criteria:

- **Scalability**:
    - Assessment of each technology's ability to increase the number of qubits and support more complex applications.
    - Includes examining system architectures and modularity.
- **Impact on Applications**:
    - Measurement of each technology's practical relevance in scientific, industrial, and educational contexts.
    - Includes areas such as logistics, molecular simulation, and teaching of fundamental quantum concepts.
- **Technological Challenges**:
    - Analysis of the main obstacles faced by each approach, such as error mitigation, maintaining quantum coherence, and hardware limitations.

IV.2 DATA COLLECTION AND ORGANIZATION

Data were collected from the following sources:

- **Scientific Articles and Reports**: Including technical information and performance updates published by companies and institutions related to these technologies [9],[10].
- **Primary Sources**: Data on IBM's quantum processors (Eagle and Condor), D-Wave's Advantage2 systems, and NMR devices such as SpinQ Gemini and Triangulum were extracted directly from technical documentation [5], [6].
- **External References**: Publications describing practical applications, such as supply chain optimization and
- educational experiments, were used [11],[12].

The data were organized into tables and graphs to facilitate comparative analysis and visualization, following the structure presented in this Section.

IV.3 ANALYSIS AND COMPARISON

Data were analyzed in three main steps:

- **Scalability**:
    - IBM leads with scalable systems, such as Condor (1121 qubits), aiming to surpass 4000 qubits by 2025.
    - D-Wave offers moderate scalability, with 1200 qubits optimized for specific problems.
    - NMR systems are limited in scalability, with a maximum capacity of 3 qubits.
- **Impact on Applications**:
    - IBM stands out in scientific and industrial applications, including material modeling and artificial intelligence.
    - D-Wave has significant impact in optimization areas, such as logistics and geophysics.
    - NMR systems mainly contribute to teaching and initial research.
- **Technological Challenges**:
    - IBM faces challenges in error mitigation and integration with classical systems.
    - D-Wave relies on hardware advancements to expand its application.
    - NMR systems have limitations in precision and coherence maintenance.

IV.4 DATA VISUALIZATION

The comparisons were synthesized into a table and a graph to illustrate the differences and complementarities of the technologies:

Table 2: Summary Comparison of Quantum Technologies

Technology	Main Focus	Scalability	Impact on Applications	Technological Challenges
IBM	Universal Computing	High	Broad scientific impact	Error mitigation
D-Wave	Optimization	Moderate	Industrial optimization	Hardware advancement
NMR	Education and Research	Low	Teaching and research	Precision limitations

Source: Authors, (2024).

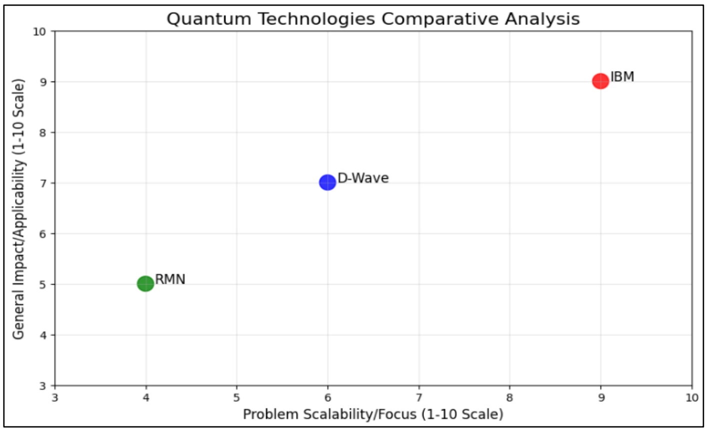

Figure 1: Comparative Analysis of Quantum Technologies.
Source: Authors, (2025).

The Figure presents a two-dimensional graph with scalability and impact criteria for the three technologies, highlighting differences in their applications and limitations. Table

2 provides a summary comparison of different quantum technologies, highlighting their main focus, scalability, impact on applications, and technological challenges. For instance, IBM focuses on universal computing with high scalability and broad scientific impact, though it faces challenges related to error mitigation. D-Wave, primarily aimed at optimization, offers moderate scalability and contributes to industrial advancements, while NMR focuses on education and research with low scalability due to precision limitations. These distinctions are further visualized in Figure 1, which plots scalability against general impact, emphasizing the varying strengths and challenges across these technologies (Table 2).

IV.5 METHODOLOGY CONCLUSION

The criteria and methods described ensure a robust analysis, enabling an understanding of how IBM, D-Wave, and NMR technologies are positioned in the current quantum landscape. The use of tables and graphs complements the analysis, providing a clear and objective view of each approach's strengths and challenges.

V. CONCLUSION

The approaches developed by IBM, D-Wave, and NMR-based systems exemplify the diverse and transformative potential of quantum computing. IBM excels in scalable solutions for complex challenges, D-Wave provides targeted tools for optimization, and NMR systems enable education and foundational research. Together, these approaches are shaping a future where quantum computing becomes a cornerstone of technological and scientific innovation. Quantum computing requires continued interdisciplinary collaboration, involving physicists, engineers, and computer scientists, to overcome its challenges. Its evolution will not only redefine problem-solving capabilities but also create new paradigms for advancing science, technology, and society.

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